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# OSCILLATIONS IN THE MAGNETIC FIELD OF THE SOLAR CORONA IN RESPONSE TO FLARES NEAR THE PHOTOSPHERE

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## ABSTRACT

The magnetic field in the outer solar atmosphere is frequently distorted by flares. In some cases, a fraction of the field exhibits a rapidly damped oscillation (Schrijver et al.; Aschwanden et al.). If this is a resonating wave trapped in the field, then the rapid damping requires a viscosity or resistivity that is at least $10^8$ times larger than expected (Nakariakov et al.). We propose instead that some of the field lines are so sensitive to the source positions that rocking motions of the photospheric plasma associated with some solar flares (Kosovichev & Zharkova) cause a few loops to oscillate in (anti)phase in the fundamental mode, with a period and decay rate that are determined largely by the characteristics of the photosphere, saying little about the high atmosphere.

*Subject headings:* Sun: activity — Sun: corona — Sun: magnetic fields

## 1. INTRODUCTION

The *Transition Region and Coronal Explorer* (*TRACE*) spacecraft offers an unprecedented resolution of the hot outer atmosphere of the Sun (Schrijver et al. 1999): the extreme-ultraviolet (EUV) radiation originating from the (1–2) × $10^6$ K coronal plasma is recorded with an angular resolution equivalent to ≈700 km on the Sun and a cadence that is often substantially faster than one exposure per minute. But although this major step forward in solar observations led to the discovery of transverse oscillations of the coronal magnetic field (Schrijver et al. 1999), only two cases of clear oscillations are known thus far: one is associated with a flare at 12:55 UT on 1998 July 14, analyzed by Aschwanden et al. (1999), the other with a flare at 08:21 UT on 1999 July 4, first reported on here.

These oscillations appear to occur in association with a coronal blast wave or rapid field reconfiguration, but the infrequency with which loop oscillations are observed implies that the process is extremely sensitive to the conditions of the trigger and to the configuration of the magnetic field. The more common coronal response to a flare is a field distortion that is followed by a rapid relaxation to the initial configuration, not infrequently leading to a Moreton-Ramsey wave that can cover part or most of the solar disk (Thompson et al. 1997; Wills-Davey & Thompson 1999). Many more examples of this response are known than of transverse field oscillations; the coronal magnetic field is apparently not easily driven to oscillate at observable amplitudes at periods of a few minutes.

The field-line (or magnetic loop) oscillations have been interpreted as a resonance of trapped waves, possibly of fast kink mode (Aschwanden et al. 1999), in essentially the fundamental resonance of the field in which the loop footpoints form the fixed nodes. If the phenomenon is indeed a coronal resonance, then the damping timescale is the most telling quantity (Nakariakov et al. 1999). Nakariakov et al. (1999) take the wave to be trapped in the coronal loop and assume that dissipation occurs only through viscous or resistive processes. The damping timescale then requires either the viscosity or the resistivity to be a factor of $10^8$–$10^9$ higher than expected on theoretical arguments (Nakariakov et al. 1999). If correct, this would ease the traditional problems with coronal heating mechanisms significantly, while requiring a substantial rethinking of our understanding of magnetohydrodynamic processes.

In this Letter, we propose an alternative mechanism for the oscillation and its rapid decay. The driving and decay in this case are determined by photospheric properties rather than the coronal resonant response.

## 2. OBSERVATIONS OF CORONAL LOOP OSCILLATIONS

Following the flare on 1998 July 14, approximately 10 distinct bundles of magnetic field lines seen in the 171 Å *TRACE* passband (characteristic of ≈$10^6$ K) were observed to oscillate (Aschwanden et al. 1999). The average peak amplitude of the oscillations was 4100 km. The periods for all these loops were close to 5 minutes, and they were in phase to within approximately 1 minute (roughly the cadence of the observing sequence) throughout the ≈15 minute interval during which the oscillations persisted.

The flare on 1999 July 4, shown in Figure 1, occurred during an orbital phase in which *TRACE* experienced background radiation that was too high for the relatively long EUV exposures, so that the initial phase was observed only at UV wavelengths. This C6 flare, in a region some 40° southeast of disk center, was first seen in the 1600 Å channel at 08:20 UT and occurred at the leading edge of the central bipolar structure (in which two groups of opposite-polarity pores temporarily coagulate into a sunspot-like configuration, but encompassing two polarities rather than one). The *TRACE* 171 Å observations resumed at 08:33 UT, i.e., after approximately one damping timescale as observed for the 1998 July 4 flare (Nakariakov et al. 1999). After that, only one oscillation is observed in a fan of loops enclosed by the two examples shown in the bottom panel of Figure 1. The period is consistent with 5 minutes but is obviously poorly determined; the observed displacements have a maximum amplitude of 3000 km (for the upper loop) to 6700 km (for the lower loop), suggesting substantially larger amplitudes in the initial phase. Interestingly, they move in anti-

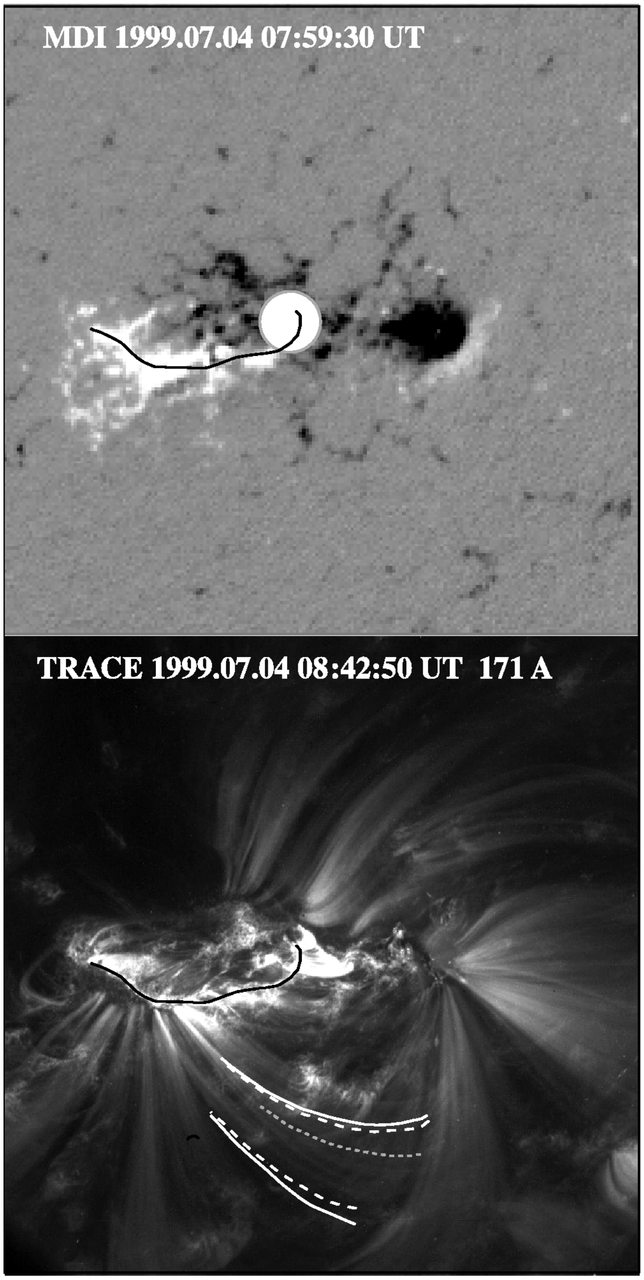


FIG. 1.—Oscillations of the magnetic field in the solar outer atmosphere. *Top*: Magnetogram (Michelson Doppler Imager [MDI] on *SOHO*). The circle marks the location of the initial flare brightening at 08:20 UT in the *TRACE* 1600 Å channel. *Bottom*: *TRACE* image in the 171 Å channel [characteristic of (1–1.5) × $10^6$ K] after oscillations have damped. The set of oscillating coronal loops is bounded by the solid white lines (at 08:36 UT). The dashed lines show the initial positions of the loops (at 08:33 UT). These two loops are in antiphase. A faint loop in between these (*dotted gray line*) is slightly out of phase with respect to the upper marked loop. The bright flare ridge, near which the oscillating loops end, is marked by a curve that is shown in both panels. The field of view has sides of 290 Mm.

phase. A faint loop between these two appears to lag slightly behind the nearby upper loop, but by no more than approximately 1 minute.

The common properties of these two instances in which oscillating loops have been seen are that (1) their periods lie close to 5 minutes, (2) the damping timescale is of order 15 minutes, and (3) the oscillations of all loops are very nearly in phase or in antiphase.

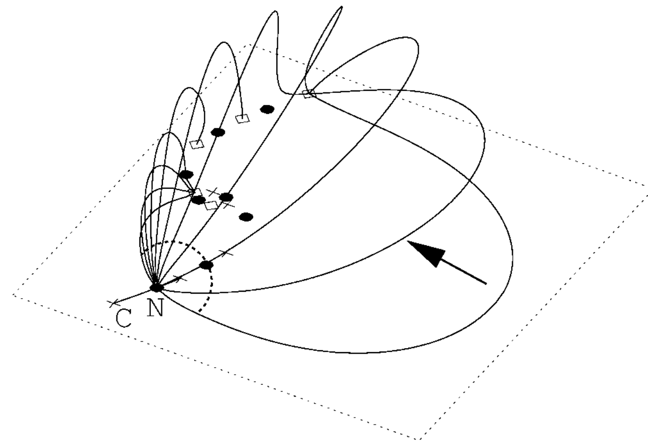


FIG. 2.—Configuration of the magnetic field susceptible to oscillations. The figure shows a simple configuration of magnetic charges in a plane; the positive sources are shown as plus signs; the negative sources are shown as open diamonds. The null points where the magnetic field vanishes are shown as filled circles. The field lines shown demarcate the surface that forms the asymptote (called the separatrix fan of null point N) for field lines from either of the two nearest charges. The two line segments in the plane connecting the null point to the charges are called spine field lines.

## 3. DISCUSSION AND CONCLUSIONS

Instead of the resonance mechanism for coronal oscillation that was proposed by Nakariakov et al. (1999), we propose an alternative scenario that offers a natural explanation for the observed timescales without invoking extraordinary coronal conditions. This mechanism relies solely on the properties of magnetic field topologies in which field lines move through space with very different velocities as the field sources are moved about (an example is shown in a movie by Priest & Schrijver 1999). We explore this process using simple vacuum potential fields; nonvacuum fields are expected to have similar properties.

For clarity, we start from a configuration of magnetic charges in a plane that crudely mimics the configurations observed for the two loop oscillations: arcs of a given polarity nested around each other in a central inversion of the polarity pattern (Fig. 2). Between the charges of like polarities, there are null points where the field goes to zero. These null points lie on what are known as the spine field lines that connect them to the nearby charges. The other mathematical extension of these spine field lines defines the separatrix (Brown & Priest 1999) that separates the domains of connectivity between the pairs of charges (Fig. 2). Typically, the two spine field lines going into a null point spread out into a surface, or fan, around the null point; this separatrix fan acts as an asymptote for field lines that lie close to the spines.

Now imagine a field line emanating from a charge (C in Fig. 2) in a direction that goes almost but not quite to the nearby null point (N), lying just slightly above the plane and to one side of the null point when seen from above (for example, one that lies close to the separatrix field line pointed out by the arrow in Fig. 2). If some of the charges in the plane move slightly, so will the null points, but the null points, the separatrices, and their intersections at separators will generally change little in position. Any field line passing close to a null point, however, will display a substantial swing in position. If the null point is moved just to the other side of the field-line direction from the source, the field line will swing very nearly across the entire separatrix dome (more or less swinging along

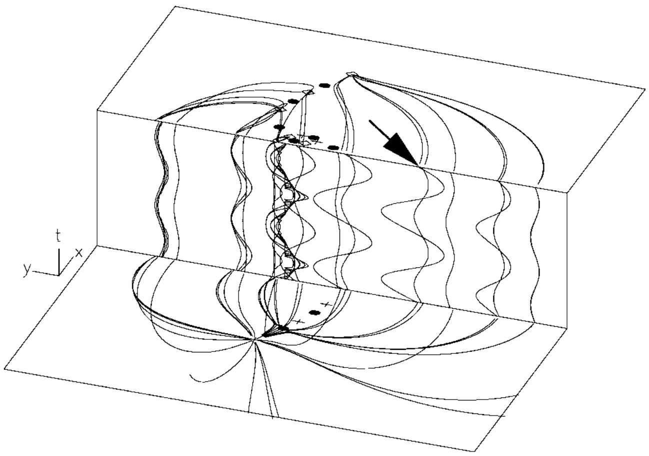


FIG. 3.—Oscillations in the magnetic field over a magnetic region on the solar surface. The horizontal plane, cut in the middle, shows the projection of lines of force in a potential magnetic field with sources as in Fig. 2 (*open diamonds and plus signs for the opposite polarities*). The vertical plane shows the temporal evolution of the field at a cut through the projection plane. Small periodic displacements of two of the central sources cause all field lines to oscillate. Those that pass close to a null point exhibit a much higher amplitude than those that give the null points a wider berth, even though they may lie close to the more strongly oscillating field lines throughout their path to an opposite charge. The oscillation of the field line marked by the arrow is shown in Fig. 4.

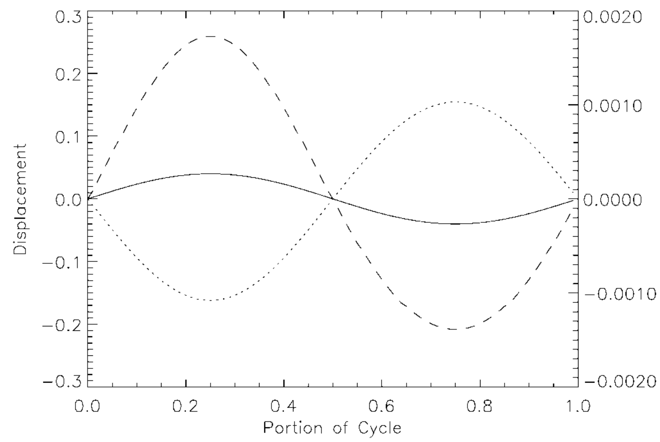


FIG. 4.—Loop oscillations in the central cut through the field, as in Fig. 3. The displacement (*dashed line*) of the magnetic field line marked by the arrow in Fig. 3, which has the largest amplitude, is 7 times larger than that of the central magnetic charges (*solid line*). The displacement of the null point (*dotted line; right-hand axis*) is almost 300 times smaller than the loop-top amplitude.

the arc indicated by the dotted line in Fig. 2). This phenomenon does not necessarily require reconnection to occur on the moving field line (Priest & Schrijver 1999), although some field lines moving ahead and/or behind them need to be involved in that process. The perturbation of the null point may be driven by the displacement of quite distant charges.

We propose that the phenomenon of oscillating loops is related to sunquakes that may be triggered by near-surface solar flares (Kosovichev & Zharkova 1998). If the flare is violent enough or the magnetic configuration favorable, a shock wave can couple to the solar surface (photosphere). Alternatively, one could imagine that a rapid topological reconfiguration in the corona causes footpoints to adjust rapidly as Lorentz forces propagate the perturbation down to the photosphere. Either way, the flare can induce a displacement of the field sources at the surface, which induces in turn an oscillatory relaxation of the field as the field rocks about in the photospheric gas. Unfortunately, at the time of the flare on 1998 July 14, the *Solar and Heliospheric Observatory* (*SOHO*) was not observing the Sun. For the flare on 1999 July 4, no significant photospheric perturbation was observed (A. Kosovichev 2000, private communication). Hence, we cannot quantify the magnitude of the oscillations that were excited. The mechanism that we propose works, however, even for relatively small displacements.

The flare that triggers the loop oscillation observed on 1999 July 4 goes off near the center of the magnetic configuration. If we oscillate the central sources of opposite polarity in our charge plane, we see that field lines passing very near to null points show much larger oscillations, whereas the others are hardly displaced at all (Fig. 3). Comparing our simulations with the scale of the observed magnetic region on the Sun, a displacement of several hundred kilometers of the magnetic charges could result in a loop oscillation with an amplitude of several thousand kilometers (Fig. 4), as is observed. In this scenario, the period of the oscillation is dominated by the photospheric oscillation (typically around 5 minutes), and the damping is simply a consequence of the propagation of the photospheric oscillation as in the case of a pebble thrown into a pond (two to three periods), as observed by Kosovichev & Zharkova (1998). The initial amplitude of 1.5 km $s^{-1}$ observed for the single sunquake observed so far is compatible with the required amplitude of a few hundred kilometers for the source displacements. The delay between the flare and the excitation of the loop oscillations is small—determined by the Alfvén speed in the corona—as indeed observed.

The real magnetic configuration is much more complex than the simplified version used to illustrate the scenario: the flux in each of the two polarities is concentrated in a multitude of flux tubes scattered over the opposite-polarity areas within the magnetic plage. Welsch & Longscope (1999) argue that within an environment of $N$ concentrations of the same polarity, there are $N - 1$ null points, provided there are no degenerate nulls caused by particular symmetries. Each of these nulls will be affected somewhat by the displacement of a charge. All displacements will be in phase with the rocking motion of a footpoint that results from a flare, but the direction of motion of a responding loop depends on the direction in which the null shifts. As a result, loops are expected to oscillate either in phase or in antiphase with others depending on the displacement of the null they approach, as is indeed observed. In the example shown in Figure 1, the loops oscillating in antiphase end at different points on a ridge. This ridge passes through the center of the trailing polarity and therefore is necessarily close to a number of different null points located between the substantial number of flux tubes in the photosphere. The larger number of nulls leads to smaller separatrix surface areas, which limits the amplitude of the loop oscillations to roughly the spacing of the null points times the expansion factor of the field between the canopy and the higher corona; the observed amplitudes of some 4000–7000 km are allowed by the expected size of the connectivity volumes for a typical spacing of some 5000 km and a field expansion of a factor of 2–3.

The interpretation of loop oscillations as a response to photospheric perturbations, amplified through null-point displacements, is supported by our initial explorations using potential fields. Other magnetic configurations may be much more sensitive to small-amplitude charge displacements, while closer packing of like-polarity charges (as is the case on the real Sun) may increase the fraction of the field involved in the process (although not many field lines should be involved, in view of the fact that loop oscillations are a rarely observed phenomenon). Further research is needed to tell what causes the rare photospheric oscillations, how large the associated displacement oscillations are, and how that perturbation propagates into the corona. Whichever explanation of the loop oscillations will prove to be correct, their study has already deepened our understanding of the solar corona. If our scenario is correct, however, the corona may not have the remarkably high viscosity or resistivity argued for by Nakariakov et al. (1999).

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